Global, regional, and national disability-adjusted life years (DALYs) for 315 diseases and injuries and healthy life expectancy (HALE) for 195 countries and territories, 1990-2015: a systematic analysis for the Global Burden of Diseases, Injuries, and Risk Factors (GBD) 2015 Study

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Summary

Background

Healthy life expectancy (HALE) and disability-adjusted life years (DALYs) provide comparable summary measures of health across geography and time that can inform macro-level assessments of epidemiological patterns and health system performance, help prioritise investments in research and development, and monitor progress toward the Sustainable Development Goals (SDGs).

Methods

We used Global Burden of Diseases, Injuries, and Risk Factors 2015 Study (GBD 2015) results on all-cause mortality, cause-specific mortality, and nonfatal disease burden to derive HALE and DALYs by sex for 195 countries and territories from 1990 to 2015. We calculated DALYs by summing years of life lost (YLLs) and years of life lived with disability (YLDs) for each geography, age group, sex, and year. We then estimated HALE using the Sullivan method, which draws from age-specific death rates and YLDs per capita. We assessed how observed levels of DALYs and HALE differed from expected trends as related to Socio-demographic Index (SDI), a composite indicator constructed using measures of income per capita, average years of schooling, and total fertility rate.

Findings

Total global DALYs remained largely unchanged from 1990 to 2015, with decreases in communicable, neonatal, maternal, and nutritional (Group 1) disease DALYs offset by increased total burden due to non-communicable diseases (NCDs). Much of this epidemiologic transition was due to changes in population growth and aging, but it was accelerated by widespread SDI improvements that also strongly correlated with increasing importance of NCDs. Both total DALYs and age-standardised DALY rates due to most Group 1 causes significantly decreased by 2015, and while total burden climbed for the majority of NCDs, many saw age-standardised DALY rates decline. Nonetheless, age-standardised DALY rates due to several high-burden NCDs—including oesteoarthritis, drug use disorders, depression, diabetes, congenital birth defects, skin, oral, and sense organ diseases—either increased or remained unchanged, leading to increases in their relative ranking in many geographies. From 2005 to 2015, HALE at birth increased by an average of 2.9 years (2.9–3.0) for men and 3.5 years (3.4–3.7) for women, while HALE at age 65 improved by 0.85 years (0.78–0.92) and 1.2 years (1.1–1.3), respectively. Rising SDI was associated with consistently higher HALE and a somewhat smaller proportion of life spent with functional health loss; however, rising SDI was related to increases in total disability. Many countries and territories in Central America and Eastern sub-Saharan Africa experienced increasingly lower rates of disease burden than expected, given their SDI. At the same time, a subset of geographies recorded a growing gap between observed and expected levels of DALYs, a trend mainly driven by rising burden due to war, interpersonal violence, and various NCDs.

Interpretation

Health is improving globally, but this means more populations are spending more time with functional health loss—an absolute expansion of morbidity. The proportion of life spent in ill health decreases somewhat with increasing SDI—a relative compression of morbidity—which supports continued efforts to elevate personal income, improve education, and limit fertility. Our analysis of DALYs, HALE, and their relationship to SDI represents a robust framework on which to benchmark geography-specific health performance and SDG progress. Country-specific drivers of disease burden, particularly for causes with higher-than-expected DALYs, should inform financial and research investments, prevention efforts, health policies, and health system improvement initiatives for all countries along the development continuum.

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Research in context

Evidence before this study

Disability-adjusted life years (DALYs), a summary measure of population health based on estimates of premature mortality and nonfatal health loss, originated from the initial Global Burden of Disease (GBD) study in 1993. DALYs, in combination with other summary measures such as healthy life expectancy (HALE), offer relatively simple yet powerful metrics against which progress and challenges in improving disease burden and extending healthy lifespans can be effectively monitored over time. Published in 2012, GBD 2010 provided updated estimates of DALYs due to 291 causes and HALE in 187 countries from 1990 to 2010. GBD 2013 extended this time series to 2013, 188 countries, and 306 causes. Novel analyses for quantifying epidemiologic transitions were introduced as part of GBD 2013, enabling a comparison of shifts in years of life lost (YLLs) and years lived with disability (YLDs) with increasing levels of development. The World Health Organization (WHO) has produced estimates of DALYs and HALE largely based off GBD 2010 and GBD 2013; however, modifications were implemented for a subset of causes, disability weights, and countries, and a normative life table of 91.9 years at birth was used for calculating YLLs.

Added value of this study

For GBD 2015, we generated estimates of HALE and DALYs for 315 causes by geography, sex, and age group from 1990 to 2015 for 195 countries and territories. We constructed a summary metric referred to as the Socio-demographic Index (SDI) based on measures of income per capita, average years of schooling, and total fertility rate. We estimated SDI for each geography-year, and characterised the average relationship for each age, sex, and cause for DALYs and HALE with SDI. Using these relationships, we calculated expected levels of DALYs, life expectancy, and HALE for each geography over time. We compared observed patterns of both DALYs and HALE with those expected on the basis of SDI alone, allowing us to explore where health gains exceeded – or lagged behind – corresponding changes in development.

Implications

Since 1990, overall health has improved in most countries, with particularly large gains occurring in the last 10 years. While improved health means longer lifespans, it also translates to more years of

functional health lost. The fraction of overall life expectancy spent in poor health is generally constant or has slightly declined in some countries, a result driven by declines in DALYs due to communicable, maternal, nutritional, and neonatal causes and increases for others, mainly non-communicable diseases. Country-specific drivers of disease burden, particularly when observed DALYs are higher than expected on the basis of SDI, should inform country-specific inquiry and action.

Introduction

Summary measures of population health are critical inputs for guiding health system investments and setting priorities at the global, regional, national, and subnational levels. The Millennium Development Goals (MDGs), which sought to reduce extreme poverty and improve health, expired in 2015, and were replaced by the 2030 Agenda for Sustainable Development, or the Sustainable Development Goals (SDGs).[1] The shift in focus from the MDGs to the SDGs reflects a broadening of the global development agenda,[2,3] expanding to include targets for non-communicable diseases (NCDs) and indicators that consider the interplay of environmental, societal, and economic factors on health.[4] Within this context, summary population health measures are advantageous, as they can easily represent progress toward SDG 3[5] – "ensure healthy lives and promote well-being for all at all ages" – and provide a metric by which comparative progress on other SDGs can be monitored. Summary measures also provide insights into whether, as societies live longer, they spend more or less of their time with functional health loss, a phenomenon known as the compression or expansion of morbidity which has profound implications for societies and the financing of health systems.

Two types of population health summary measures exist: health expectancies and health gaps.[6] Healthy life expectancy (HALE), which originates from Sullivan,[7] provides a single summary measure of population health by weighting years lived with a measure of functional health loss experienced before death. Many health expectancy measures have been proposed, but HALE is the only one which captures a full range of functional health loss.[8–10] Health gap measures capture differences between a population and some normative standard such as a maximum lifespan in full health. Disability-adjusted life year (DALY) is a widely used gap measure,[6,9–11] representing the sum of years of life lost (YLLs) due to premature mortality and years lived with disability (YLDs). YLLs quantify the gap between observed mortality and a normative life expectancy,[12] and YLDs capture the prevalence of conditions that lead to nonfatal health loss while accounting for the severity of those conditions. Health gap measures can be easily disaggregated to examine contributions of relative morbidity and mortality, individual diseases, injuries, and attributable risk factors.

The Global Burden of Diseases, Injuries, and Risk Factors (GBD) study is the most comprehensive source of comparable summary population health measures due to its inclusion of country-level results, uncertainty quantification, and its effort to maximise comparability across geography, time, and across different health conditions. Alternative summary health assessments are not as standardized or comprehensive, with studies only reporting incomplete time series, no uncertainty, or only a subset of countries and causes;[13,14] [15] The World Health Organization (WHO) published DALY estimates for two years (2000 and 2012), 132 causes, and 174 countries, without uncertainty. These estimates were primarily derived from GBD 2010 results, but were modified in 60 countries and for 12 cause groups separately estimated by WHO and UN agencies.[13,16,17] WHO applied the same approach for GBD 2013 results and used their own life tables to produce HALE estimates for 2015.[14] The European Commission (EC) and the Organisation for Economic Co-operation and Development (OECD) also reported healthy

life expectancy estimates for European countries from 2004 through 2014, but based on self-reported health status.[18,19]

In this paper we present GBD 2015 findings for DALYs and HALE, building upon updated estimates of mortality, causes of death, and nonfatal health loss.[12,20] Overall analytic approaches are similar to previous GBD studies,[9,10] with the inclusion of new mortality and morbidity data, refinement of methods, and expanded geographies.[12,20] This report supersedes all prior GBD studies on DALYs and HALE through the estimation of a complete time series for 1990 to 2015. To facilitate a more in-depth examination of the drivers of DALY and HALE trends, we assess how HALE along with overall and cause-specific DALYs change as geographies move through the development continuum. We use this analysis to benchmark overall progress and decompose observed disease burden compared to levels expected for specific causes on the basis of development alone to highlight potential areas for policy investment or further research.

Methods

Overview

Detailed methods for estimating DALYs and HALE, including analytic approaches for mortality and nonfatal health loss estimation, are provided in related publications.[12,20] Additional detail on GBD metrics and definitions are found elsewhere.[21] Interactive visualisation tools are also available to explore GBD 2015 results (http://vizhub.healthdata.org/gbd-compare/) and data sources (http://http://ghdx.healthdata.org/). This analysis follows the Guidelines for Accurate and Transparent Health Estimates Reporting (GATHER), which includes recommendations on documentation of data sources, estimation methods, and statistical analysis.[22,23]

In brief, the GBD geographic hierarchy involves 519 total geographies within 195 countries and territories, 21 regions, and seven super-regions. This study reports results for all countries and territories. The GBD cause hierarchy has four levels of classification and causes reported within each level that are mutually exclusive and collectively exhaustive. The full GBD cause list with corresponding International Classification of Diseases (ICD)-9 and ICD-10 codes are available in our publications on cause-specific mortality[12] and nonfatal health outcomes.[20]

Estimation of mortality and nonfatal health loss

We estimated all-cause and cause-specific mortality with a multi-step computation process, which included systematically addressing known data challenges – such as different coding schemes, different age group reporting, variation in certification, misclassification of HIV/AIDS deaths in some countries, misclassification of maternal HIV/AIDS deaths, and incorporation of population-based cancer registry data – before computation of cause-specific mortality with analytic tools such as cause-of-death ensemble modeling (CODEm). Each death can have only one underlying cause. Additional detail, including model specifications and data availability for each cause-specific model, can be found in the appendix of the GBD 2015 mortality and causes of death publication.[12] We calculated normative life tables based on the lowest death rates for each age group among geographies with total populations greater than five million. We computed cause-specific YLLs by multiplying cause-specific deaths by the life expectancy at the age of death (i.e., 86.59 years at age 0, 23.79 years at age 65) from this normative life table, and then used the GBD world population age standard to calculate age-standardised mortality rates and YLL rates.[12]

Our most commonly used analytic approach for estimating nonfatal health loss was DisMod-MR 2.1, a Bayesian meta-regression tool that synthesises diverse data sources to produce internally consistent estimates of incidence, prevalence, remission, and excess mortality. The use of other methods for estimating nonfatal health loss were determined by cause-specific data availability and epidemiological characteristics.[24] Additional detail, including model specifications and data availability for each cause-specific model, can be found in the appendix of the GBD 2015 nonfatal publication.[20] Each nonfatal sequela was estimated separately. We then applied a microsimulation framework to assess the occurrence of comorbidity in each age group, sex, geography, and year separately. Disability from comorbid conditions was apportioned to each of the contributing causes. GBD disability weights were based on population surveys with over 60,000 respondents, and previous studies show that disability weights do not significantly vary across geographies, income, or educational attainment.[25,26] In this study, disability weights are invariant over geography and time, although the distribution of sequelae – and therefore the severity and cumulative disability per case of a condition – may be different by age, sex, geography, and year.

Estimation of DALYs, HALE, and corresponding uncertainty

DALYs are the sum of YLLs and YLDs as estimated in GBD 2015 for each cause, geography, age group, sex, and year.[12,20] Using methods developed by Sullivan,[7] we calculated HALE by age group within abridged multiple-decrement life tables and estimates of YLDs per capita for each geography-age-sex-year from 1990 to 2015.[8,10,27]

For all results, we report 95% uncertainty intervals (UIs), which were derived from 1,000 draws from the posterior distribution of each step in the estimation process. UIs are distinct from confidence intervals, as the latter only capture the uncertainty associated with sampling error, while the former provide a method for propagation of uncertainty from multiple sources including sampling, model estimation and model specification. Ninety-five percent UIs represent the ordinal 25th and 975th draw of the quantity of interest. For mortality and YLLs, UIs reflect uncertainty that arises from sample sizes of studies used as data sources, adjustments to sources of all-cause mortality, parameter uncertainty in model estimation and specification uncertainty for all-cause and cause-specific models. For prevalence, incidence and YLDs, UIs reflect uncertainty that arises from sample sizes of studies used as data sources, data adjustments from non-reference definitions, parameter uncertainty in model estimation and uncertainty in the disability weights. For DALYs and HALE, in the absence of any direction information on the correlation between uncertainty in YLLs and YLDs, we assumed uncertainty in age-specific YLDs is independent of age-specific YLLs and death rates, respectively.

Epidemiologic transition and relationship between DALYs, HALE, and SDI

We examined the relationship between DALYs, HALE, and the Socio-demographic Index (SDI).[28] SDI was constructed based on the geometric mean of three indicators: income per capita, average years of schooling among populations aged 15 or older, and the total fertility rate (TFR). SDI values were scaled to a range of 0 to 1, with 0 equaling the lowest income, lowest schooling, and highest TFR observed from 1980 to 2015, and 1 equaling the highest income, highest schooling, and lowest TFR assessed during that time. The average relationships between each summary health measure and SDI were estimated using spline regressions. These regressions were used to estimate expected values at each level of SDI. Additional detail on SDI computation and geography-specific SDI values are available in the appendix.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

Global trends for DALYs and HALE

Figure 1 charts global trends for numbers, all-age rates and age-standardized rates for global DALYs divided into Level 1 causes. All-age rates account for the effects of population growth while age-standardisation further adjusts for changes in age structure. Total Group 1 DALYs fell from 1.2 billion (1.2–1.2 billion) in 1990 to 746.1 million (703.9–787.7 million) in 2015 (Figure 1), whereas total DALYs from NCDs increased from 1.1 billion (1.0–1.2 billion) in 1990 to 1.5 billion (1.3–1.7 billion) in 2015. Total injury DALYs remained relatively unchanged between 1990 and 2015. All-age DALY rates (Figure 1) for NCD remain flat while for Group 1 they declined substantially. Taking into account aging, Group 1 causes steadily fell and NCDs decreased as well (Figure 1). For injuries, reductions in all-age DALY rates and age-standardised DALY rates were quite similar between 1990 and 2015.

At the global level, HALE at birth increased to 60.9 years (58.6–63.0) for men and 64.9 years (62.0–67.5) for women in 2015, rising 2.9 years and 3.5 years since 2005, respectively. The gap between life expectancy and HALE, which represents years of functional health lost, widened between 2005 and 2015 from 7.7 to 8.1 years for men and 9.4 to 10.0 years for women. Globally, life expectancy at age 65 was 18.5 years (18.3–18.6) for women and 15.5 years (15.3–15.6) for men, while HALE was 14.2 years (13.0–15.3) and 11.9 years (10.9–12.8) for each sex, respectively.

Global causes of DALYs

In 2015, Group 1 causes accounted for 29.1% (27.7–30.6%) of global DALYs, NCDs led to 61.1% (59.3–62.8%), and injuries caused 9.8% (9.2–10.4%) (Table 1). Since 2005, DALYs for many of the world's leading communicable causes substantially declined, yet for a subset of infectious diseases burden increased. Age-standardised DALY rates from HIV/AIDS and malaria each fell more than 40%, while other high-burden infectious diseases, namely lower respiratory infections (LRIs) and diarrhoeal diseases, recorded decreases in total and age-standardised rates of DALYs that exceeded 20%. From 2005 to 2015, reductions in both total and age-standardised rates of burden due to tetanus and measles surpassed 50% and 70%. African trypanosomiasis, a disease targeted for elimination, saw both total DALYs and age-standardised rates fall more than 70% since 2005. DALY rates substantially fell for all types of hepatitis, with age-standardised DALY rates from acute hepatitis A declining more than 35% by 2015. However, both total DALYs and age-standardised DALY rates from dengue increased by more than 50%. While the West African Ebola outbreak peaked in 2014,[29] Ebola still caused burden in 2015. Maternal disorders significantly declined from 2005 to 2015, with total DALYs and age-standardised rates each falling more than 20%. Reductions in the global burden of neonatal disorders were somewhat less pronounced; for instance, neonatal sepsis burden was largely unchanged.

In 2015, cardiovascular diseases (CVD), cancers, and mental and substance use disorders were among the leading causes of NCD burden. For many NCDs, including most cardiovascular causes and most cancers, total DALYs increased but age-standardised DALY rates declined. Nearly all neurological disorders increased in total DALYs, including Alzheimer disease and other dementias, which rose more

than 30%, whereas age-standardised rates either moderately decreased (e.g., Alzheimer disease and other dementias) or were relatively unchanged (e.g., Parkinson's disease). Total DALYs from low back and neck pain also increased, rising more than 17%. Cirrhosis caused more DALYs in 2015 than in 2005, though age-standardised DALY rates significantly fell. A similar overall trend was found for diabetes and chronic kidney disease (CKD), with all aetiologies but CKD due to diabetes, recording significant declines in age-standardised DALY rates amid rising total DALYs. For other NCDs, namely those associated with skin diseases, sensory conditions, and oral disorders, total DALYs significantly increased from 2005 to 2015, and age-standardised DALY rates either somewhat increased or did not significantly change since 2005. Age-standardised DALY rates from chronic obstructive pulmonary disease (COPD) fell more than 20% from 2005 to 2015, while asthma decreased almost 17%. Peptic ulcer disease, a leading cause of digestive disease burden, saw marked reductions in total DALYs and age-standardised DALY rates, with the latter decreasing nearly 30%.

Since 2005, a number of NCDs significantly increased in terms of total burden and age-standardised DALY rates. Osteoarthritis was the most notable example, with total DALYs and age-standardised DALY rates rising 34.8% (33.6–36.0%) and 3.9% (3.0–4.8%), respectively. Major depressive disorders and drug use disorders – particularly opioids and cocaine – both increased in total DALYs and age-standardised rates; however, age-standardised DALY rates from alcohol use disorders dropped 18.5% (15.1–22.0%). Total DALYs and age-standardised DALY rates from CKD due to diabetes also significantly increased by 2015. Male and female infertility accounted for a relatively small fraction of NCDs, but burden due to both causes increased significantly since 2005. Oral disorders and sense organ diseases also saw increasing total DALYs, whereas their age-standardised DALY rates remained relatively unchanged since 2005.

Injuries

Unintentional injuries and transport injuries each saw age-standardised DALY rates significantly decrease (19.5% [15.3–22.2%] and 17.4% [13.5–21.6%], respectively). Road injury burden significantly declined since 2005, with age-standardised DALY rates falling 17.6% (13.8–21.8%) by 2015. Among unintentional injuries, drowning experienced the largest reduction in both total burden (26.2% [20.0–30.6%]) and age-standardised DALY rates (32.3% [26.7–36.3%]). Age-standardised DALY rates from self-harm and interpersonal violence both fell more than 16% since 2005. DALYs due to forces of nature, war, and legal intervention increased from 2005 to 2015, though not significantly; this rise was primarily driven by escalated violence and war in the Middle East. Despite still causing major health loss in 2015, forces of nature caused far fewer DALYs than in 2005, mainly because there were no large-scale losses of life like seen in the 2005 earthquake that killed more than 70,000 in India and Pakistan.

Changes in leading causes of disease burden over time

Figure 2 compares relative ranks and changes in total DALYs, all-age DALY rates, and age-standardised DALY rates by cause from 1990 to 2005 and 2005 to 2015. In 1990, LRIs, preterm birth complications, and diarrhoeal diseases were the three leading causes of burden; by 2015, only LRIs remained among the leading three causes of DALYs worldwide. Many Group 1 causes saw significant declines for total burden, as well as all-age DALY rates and age-standardised DALY rates, for both time periods; these causes included tuberculosis, meningitis, diarrhoeal diseases, protein-energy malnutrition, preterm birth complications, tetanus, and measles. Such reductions across measures of DALYs contributed to downward shifts in relative ranks for most Group 1 causes over time. Malaria and HIV/AIDS both

diverged from this trend, with each recording large increases in burden from 1990 to 2005, but by 2015, all measures of DALYs and relative ranks for malaria and HIV/AIDS fell markedly. Trends for NCDs and injuries, both in terms of ranks and changes in disease burden, were more varied. Between 1990 and 2005, total DALYs and all-age DALY rates significantly increased for many NCDs, including IHD, low back and neck pain, lung cancer, CKD, and migraine. For these NCDs, their relative ranks also climbed by 2005, yet their age-standardised DALY rates either significantly decreased or remained relatively unchanged, reflecting the effects of changes in population age structure. This pattern continued through 2015 for many NCDs, and was further exemplified by Alzheimer's disease and other dementias as it rose to the twenty-ninth leading cause of global DALYs amid a significant decrease in age-standardised DALY rates. Particularly from 1990 to 2005, all three measures of DALYs significantly increased for a subset of NCDs (ie, sense organ diseases, diabetes, depressive disorders, and other musculoskeletal disorders), which contributed to their rises in relative ranking. More heterogeneous patterns emerged for injuries; for instance, road injuries and interpersonal violence each rose in reflective ranks from 2005 to 2015 despite significant reductions in total DALYs, all-age DALY rates, and age-standardised DALY rates from each causes.

For at least one of their leading causes of DALYs in 2015, most age groups under 40 saw total burden decrease more than 31% (Figure 3). These causes for which DALYs largely declined included LRIs, diarrhoeal diseases, malaria, preterm birth complications, and drowning among populations under 5, and HIV/AIDS, and Malaria for populations between the ages of 5 and 40. Increases in cause-specific DALYs varied more by age group, with burden from depressive disorders and drug use disorders rising for populations between the age of 20 and 30 years. DALYs from low back and neck pain increased since 2005 for many age groups. For populations 60 and older, several causes, including IHD, CKD, diabetes, hearing loss, and Alzheimer's disease and other dementias, ranked among the leading causes of DALYs in 2015 and caused more burden than in 2005.

Regional and country-specific HALE

HALE at birth was highest for men in Singapore (72.3 years [70.1–74.2]) and for women in Andorra (76.3 years [72.8–79.4]) in 2015. It was lowest in Lesotho for both men (39.1 years [34.3–44.7]) and women (43.8 years [37.9–49.8]) (Table 2) – see appendix table 2 for results for all GBD years. HALE at birth in 2015 exceeded 70 years in only 14 geographies for men, while 59 countries and territories surpassed this threshold for women. Thirteen countries and territories had HALE below 50 years for either sex. Since 2005, 121 countries and territories saw significant increases in HALE at birth for men and 139 for women, led in both cases by Zimbabwe, while HALE at birth worsened for two countries – Syria and Libya – driven primarily by decreases in life expectancy. HALE at age 65 was highest in Andorra for both men (15.2 years [13.9–16.3]) and women (19.4 years [17.8–20.8]) in 2015, while Lesotho was the lowest for men (6.9 years [5.2–9.4]) and Afghanistan for women (6.9 years [5.8–8.2]).

Epidemiological transition

For all panels in Figure 4, each icon represents a successive year from 1990 to 2015, for each GBD region. The black line denotes expected levels based on the average historical relationship with rising SDI. Icons appearing above the black line for HALE represent better than expected healthy life expectancy on the basis of SDI alone.

HALE at birth increased continuously and in a largely linear manner with increasing SDI for both sexes (Figure 4A). At an SDI of 0.20, average HALE was 46.2 years for men and 47.1 years for women and by an SDI of 0.90, average HALE was 69.8 years for men and 73.8 years for women. Among high SDI regions, North America was the furthest below expected HALE at birth for both sexes, while high-income Asia Pacific remained above expected HALE at birth for both sexes and over time. In Australasia, male HALE consistently tracked expected levels whereas female HALE remained below expected levels since 1990. With the exception of the Caribbean in 2010 – the year of the Haitian earthquake – HALE at birth throughout Latin America and the Caribbean generally was higher than expected levels for both sexes. HALE at birth also exceeded expectations in East Asia and North Africa and the Middle East. By contrast, Oceania steadily remained below expected levels of HALE, and all regions within the Central Europe, Eastern Europe, and Central Asia GBD super-region had HALE lower than expected over time, particularly for men. HALE trends in sub-Saharan Africa were heavily influenced by the HIV/AIDS epidemic, particularly in Southern sub-Saharan Africa, where HALE was well below expected levels on the basis of SDI. Notably, after lagging below expected levels of HALE prior to 2005, Eastern sub-Saharan Africa posted average HALE for women that exceeded expected levels. Less pronounced increases occurred for men in Eastern sub-Saharan Africa, as HALE essentially equaled expected levels only around 2010.

Years of functional health lost on average increased as countries developed (Figure 4B). Among high-income regions, all regions except for high-income Asia Pacific consistently exceeded expected levels of functional health loss over time, and women generally experienced a higher gap than men. South Asia, North Africa and the Middle East, and Central sub-Saharan Africa generally experienced higher-than-expected functional health loss on the basis of SDI, whereas a number of regions, including Oceania, Southeast Asia, and East Asia all recorded smaller gaps between life expectancy and HALE than expected.

The ratio of years of functional health loss to life expectancy – the proportion of life expectancy spent with disability – declined slightly with increasing SDI (Figure 4C). Among men and women, Central sub-Saharan Africa had the highest proportion of life spent with disability in 2015, though high-income North America experienced the largest difference between observed and expected levels for that year. For both sexes, several regions showed higher-than-expected proportions of life expectancy spent in ill health (eg South Asia, North Africa and the Middle East, and Australasia), while others experienced lower-than-expected levels over time (eg Southeast Asia, East Asia, Eastern sub-Saharan Africa, and Southern Latin America).

Figure 5A and 5B summarize the expected pattern of the epidemiological transition as populations move through the development continuum based on the historical data available from 1990 to 2015. Age-standardized YLL rates for many communicable causes, neonatal conditions, and neonatal conditions decline profoundly as SDI increases. At the same time, age-standardised YLD rates for the leading causes of YLDs such as mental and substance abuse disorders and musculoskeletal disorders demonstrate relatively little change. At higher levels of SDI, the composition of disease burden shifted toward YLDs as the primary driver burden, mainly due to the differential pace of change. The combined effect of the change in age-specific rates and age-structure change that occur with development is shown in Figure 5B which provides all-age YLL and YLD rates for Level 2 causes. Demographic shifts in age-structure potentiate and accelerate the transition from Group I conditions toward NCDs in terms of the composition of the burden of disease that health systems must handle. Of note, from an SDI of 0.8

onwards further declines in the age-standardized rates are matched or exceeded by increases in population age structure so that all-age rates for YLDs actually increase, as do YLL rates for some causes such as neurological conditions. These characterisations of the epidemiological transition demonstrate the "double burden of communicable diseases and NCDs" for populations with an SDI in the intermediate range.

Observed versus expected total and cause-specific burden

Figure 6 illustrates differences in the ratio of observed all-ages DALY rates to expected levels, on the basis of SDI alone, in 2015. Ratios are colour-coded in terms of the magnitude of differences between observed and expected all-ages DALY rates. Blues indicate much lower observed DALYs than expected levels based on SDI (ie, a ratio equal to or below 0.63), whereas reds reflect that observed DALYs far exceed expected levels given SDI (ie, a ratio above 2.49); shades of green, yellow, and orange represent the spectrum of computed ratios of observed to expected DALYs. In 2015, the Maldives and Nicaragua had the lowest ratios of observed to expected all-ages DALY rates, on the basis of SDI; many countries throughout Latin America also experienced lower-than-expected all-ages DALY rates. Other regions where observed all-ages DALY rates fell below expected levels, on the basis of SDI, included Western Europe (eg, Portugal, Spain, France, Italy, and Sweden); Western sub-Saharan Africa (eg, Burkina Faso, Niger, and Senegal); Eastern sub-Saharan Africa (eg, Burundi and Ethiopia); North Africa and the Middle East (eg, Jordan, Saudi Arabia, and Turkey); East Asia (eg, China); and a subset of countries in South and Southeast Asia (eg, Bangladesh, Sri Lanka, and Vietnam). By contrast, observed all-ages DALY rates exceeded expected levels, based on SDI, in Southern sub-Saharan Africa, much of Central Asia and Eastern Europe, and a number of countries in Central sub-Saharan Africa. Notably, observed all-ages DALY rates surpassed expected levels in the United States (US).

Figure 7 displays ratios of observed to expected total DALYs, on the basis of SDI alone, for the leading 10 causes of total DALYs in 2015; this figure draws from the same scale and colour-coding scheme as Figure 6. IHD and stroke were the leading two causes of DALYs worldwide in 2015, and 106 geographies also had one of these diseases as the leading cause of DALYs that year. Four GBD super-regions showed deviations from this trend: Latin America and the Caribbean, where diabetes and interpersonal violence often resulted in the most DALYs; North Africa and the Middle East, where war was a primary cause of burden; South Asia, where neonatal disorders often ranked among the leading causes of DALYs; and sub-Saharan Africa, where HIV/AIDS or malaria was the leading driver of disease burden in 29 geographies.

Stroke resulted in the most countries (94) experiencing lower observed DALYs than expected on the basis of SDI. Other leading causes for which observed DALYs were well below expected levels included IHD particularly in Latin America, East Asia, and Southeast Asia; road injuries in North Africa and the Middle East; and LRI and diarrhoeal diseases in sub-Saharan Africa. Many high-income geographies also saw lower-than-expected DALYs from IHD and Alzheimer's disease and other dementias. Road injuries accounted for less burden than expected in 52 countries and territories, especially in Colombia. Although many Group 1 causes remained among the leading causes of DALYs, observed levels were often lower than expected, on the basis of SDI (eg, LRIs in Ethiopia; diarrhoeal diseases in Afghanistan; preterm birth complications in Kenya).

By contrast, diabetes was a leading cause for which observed burden exceeded expected levels in many geographies, especially in Oceania and the Caribbean. Observed DALYs due to COPD were higher than

expected in 30 geographies, as were liver cancer and lung cancer for a subset of countries and territories. Drug use disorders led to more observed DALYs than expected, on the basis of SDI, in many high-income countries in 2015, particularly in the US and Australia. A similar pattern occurred for self-harm, cirrhosis, alcohol use disorders, and drug use disorders throughout Eastern Europe, and most prominently in Russia. Interpersonal violence was among the leading two causes of DALYs for six out of 11 countries in Central and Tropical Latin America (Brazil, Colombia, El Salvador, Guatemala, Honduras, and Venezuela), and each experienced observed burden far surpassing expected levels. Throughout sub-Saharan Africa, HIV/AIDS and malaria resulted in far more DALYs than expected, on the basis of SDI.

Heterogeneous trends across and within regions emerged in terms of both leading causes of DALYs and ratios of observed to expected levels. For instance, South Asia's disease burden landscape diverged from global patterns, with both IHD and neonatal disorders ranking among some of the leading causes of burden and often resulting in higher-than-expected DALYs on the basis of SDI. Stroke and LRIs resulted in fewer DALYs than expected for most countries in South Asia, yet other causes exacted more DALYs than expected on the basis of SDI (eg, TB in India and drowning in Bangladesh). Further, the 2015 Nepal earthquake resulted in forces of nature being its leading cause DALYs that year. Many countries in Central Asia experienced observed DALYs that surpassed expected levels due to both Group 1 causes (eg, LRIs, preterm birth complications, and neonatal encephalopathy) and NCDs such as hypertensive heart disease. War was the leading cause of DALYs in five countries in North Africa and the Middle East in 2015, including Afghanistan, Iraq, Libya, Syria, and Yemen. While neonatal sepsis frequently led to higher-than-expected DALYs in sub-Saharan Africa, burden from preterm birth complications fell below expected levels, on the basis of SDI, in most countries. Notably, NCDs such as diabetes ranked among the leading 10 causes of DALYs for a subset of countries in sub-Saharan Africa (eg, South Africa), while nutritional deficiencies also remained among leading causes of burden in others (eg, Ghana and Zimbabwe); in both instances, observed DALYs generally exceeded expected levels on the basis of SDI.

Discussion

Summary

GBD 2015 results show that the world has, on aggregate, become healthier in the last 25 years. Yet, this progress has not been universal. From 1990 to 2015, global HALE at birth increased from 56.7 years (54.3-58.8) to 62.8 years (60.2-65.2), with 191 of 199 geographies recording improved HALE. Since 1990, global HALE at age 65 also improved 1.8 years, with 179 geographies experiencing an increase in HALE at 65 as well. The global number of years of functional health lost grew during this time, from 8.2 years to 9.1 years. With YLL rates falling at a much faster pace than YLD rates, nonfatal health loss accounted for an increasing proportion of global DALYs, rising from 21.2% in 1990 to 32.1% in 2015. Worldwide progress was largely driven by rapid reductions in DALYs from communicable, maternal, neonatal, and nutritional diseases, though declines in age-standardised DALY rates from NCDs and injuries also contributed to overarching gains. Despite reductions in age-standardised DALY rates, 137 causes saw statistically significant increases in total DALYs since 2005 – a trend with extensive implications for health systems. Mental and substance use disorders, musculoskeletal disorders, and an array of other conditions including idiopathic developmental intellectual disability, vision and hearing impairment, and neurological disorders all saw rising burden since 2005, and few saw any evidence of declining age-specific YLD rates.

Compression of morbidity, SDI, and the grand convergence

Considerable research and policy attention has considered the existence of compression of morbidity, or whether people live healthier lives as their lifespans extend.[30] Beyond its profound consequences for financing health systems, compression of morbidity has considerable implications for societal structures and expectations about longevity of careers or timing of retirement. Compression can be interpreted in both absolute and relative terms. The absolute interpretation is that as people live longer lives, they lose fewer years due to functional health loss, whereas relative compression implies that as people live longer lives, the ratio of years of functional health lost to life expectancy declines. While some evidence shows that compression occurs among people with specific diseases such as diabetes and dementia,[31,32] national studies show more mixed results.[33–35] This may not be surprising, as most national studies rely on self-reported health status and chronic conditions, which are then further complicated by variations in how individuals may use the response scales and profound framing effects.[36–39] By contrast, the GBD study provides a more comprehensive and comparable assessment of changes in functional health status by synthesising many types of data, by cause, and applying standardised disability weights to reflect the public's average views of severity of different conditions. GBD 2015 results unequivocally show that as life expectancy increases people spend more time with reduced functional health status, and thus absolute expansion of morbidity has occurred. This trend is driven by marked declines in age-specific mortality at the same time minimal improvement, if any, has occurred for age-specific YLDs per capita. The proportion of lifespans spent in ill health has remained comparatively constant since 1990, and did not vary as a function of SDI; thus, we found nominal evidence of relative compression at the global level.

Drawing from our empirical characterisation of epidemiological transitions on the basis of SDI, we found that life expectancy and HALE increased linearly with SDI, whereas years of functional health lost climbed with rising SDI. Historically, increases in SDI are associated with a rapid decrease in burden from communicable, neonatal, maternal, and nutritional diseases causes – the leading killers of children, adolescent girls, and women. Efforts to increase income, provide more years of education, and reduce adolescent and total fertility rates thus may catalyse additional gains for life expectancy, HALE, and reduced disease burden, emphasising the critical role of policy interventions beyond more traditional health service delivery.

At different locations in this continuous process of change, we see evidence of a "double burden" of disease: from an SDI of approximately 0.35 to 0.60, we expect that NCDs and Group 1 causes to each account for at least 20% of disease burden. The average relationships with SDI imply that within a country where there are wide inequalities in SDI, we should also expect wide variation in disease burden patterns. Subnational disparities may be consistent with variations in subnational SDI, either recording higher or lower burden than that of the national level. Using the average patterns can help benchmark a country against others, but such assessments can also help provide insights as to whether public action or other factors are helping make inequalities narrower than expected based on SDI alone. Given the complexity of health patterns identified for many causes and differential patterns by age and sex, providing some understanding of expected patterns on the basis of SDI alone can help anchor the exploration of results and may provide some measure of the performance of health systems or the magnitude of avertable burden within each country or territory.

The Lancet Commission on Investing in Health galvanised considerable interest in the notion of a "grand convergence," such that levels of under-5 mortality, maternal mortality, and some infectious diseases could converge across all countries within a generation.[40] Convergence can be achieved through progress on increasing SDI (ie, elevating per-capita income and average years of schooling, and reducing fertility) and reducing or inverting high ratios between observed and expected (on the basis of SDI alone) health expectancies and health gaps. The Commission has argued that, within a generation, preventable deaths in children and mothers could largely be avoided through increased investment of development assistance for health and expanded national expenditure on health. The vision inspired some of the absolute threshold SDG targets, including reducing under-5 mortality to 25 deaths per 1,000 live births, neonatal mortality to 12 deaths per 1,000 live births, and maternal mortality ratio of 70 deaths per 100,000 live births for the maternal mortality ratio. The relationships between these health outcomes, broader health measures, and SDI offer a framework by which the likelihood of such a grand convergence can be assessed. Based on GBD 2015 results, the historical relationship between SDI and health suggests that convergence in the sense of reduced absolute differences in rates is likely to occur with faster improvements in SDI. If, however, convergence means smaller relative differences, then improvements in SDI alone may not be sufficient. Our findings show that continued SDI improvement does not appear to be historically associated with absolute convergence in LE or HALE. The Lancet Commission also emphasised the importance of hastening progress through strategic investments by donors and governments in effective health technologies, an approach that has the potential to catalyse faster progress than what would be expected on the basis of SDI alone. Convergence in this scenario could then be interpreted as reduction in the ratio of observed to expected burden on the basis of SDI alone for low- and lower-middle-income countries (LMICs), and could be used as an indirect, but summary, metric to monitor health system performance and overall progress toward the SDGs. Since history provides a perspective for identifying which countries have been able to reduce their ratio of observed to expected health outcomes, the comprehensive and longitudinal approach of the GBD is optimally suited for monitoring health system-driven convergence at a macro level. The same tools can also therefore be used to generate insights on progress – or lack thereof – on specific diseases and outcomes of interest. In some cases, there may be historical or geographical explanations for high burden for some conditions. In other cases, effective preventive and treatment measures have just not yet been implemented or are not functioning effectively.

Policy implications of DALYs and HALE in the SDG era

Shifting from the MDGs to the SDGs dramatically broadened the global health agenda.[2,3] The SDGs include a total of 17 goals, 169 total targets, and 230 indicators; of these measures, 11 goals, 28 targets, and 46 indicators are health-related.[41] At present, 33 of the 46 health-related indicators are measured by the GBD study. Amid earlier discussions and negotiations over SDG 3 indicators, HALE was proposed as an indicator of overarching health status and progress;[2] this proposal was not ultimately adopted in the final set of indicators. HALE provides a strong summary measure of overall health status, as it accounts for functional health loss in addition to age-specific mortality. Other summary development measures, such as the Human Development Index, have considered replacing life expectancy with HALE as an input to the overall assessment.[42] The GBD study currently, and its annual iterations going forward, measures health outcomes that are both amenable to intervention and could be risk-standardised, thus offering a useful set of metrics for monitoring progress toward specific SDG targets, such as Target 3.8's aim of achieving effective universal health coverage.

DALYs and other health gap metrics are one of many potential inputs for setting health policy and investment priorities, but major research organisations and funders such as the US National Institutes of Health and others indicate the use of DALYs to inform budgeting decisions.[43–46] Beyond health metrics, many other inputs are required for decision-making, ranging from the effectiveness of different adoptable policies and programs to key social, cultural, and ethical considerations. Nonetheless, DALYs and other summary health measures may have an even more prominent role for setting research and development priorities within the health sector, particularly in the absence of robust information on the effectiveness or likely success of various research projects and programs.[47] As global health research funders more frequently use DALYs to shape priority-setting processes, health challenges faced by populations with less health care market power – namely the poor – will inevitably surface and receive more attention. Shifting to the use of disease burden for program design and evaluation would benefit the poor, but also potentially increase overall efficiency of health research.[48] For instance, those who suffer from historically under-funded conditions – such as mental health disorders, substance use, and musculoskeletal conditions – would benefit from the greater use of DALYs in decision-making processes.

Cause-specific successes and challenges

Global progress has been especially rapid in reducing disease burden due to a number of communicable diseases, including diarrhoeal diseases, LRI, TB, syphilis, typhoid, paratyphoid, and vaccine-preventable infections such as hepatitis B, measles, tetanus, and Hib. To these successes, the last decade has seen profound declines in the burden from malaria and HIV/AIDS. NCD trends have been much more complicated. For the leading cause of disability, low back and neck pain, a lack of knowledge about risks limits the opportunity for prevention. Occupational ergonomic factors and high body mass index (BMI) are estimated to be responsible for 29.2% and 5.9% of YLDs due to low back pain, respectively.[49] The highest occupational risk is found in service industries and manual labor, especially agriculture.[50,51] The relatively small proportion of low back pain due to high BMI is amenable to intervention, but the continued escalation of obesity rates indicates that these measures may have limited effectiveness. With increasing SDI one would also expect the proportion of the workforce in agriculture to become smaller and thus have some impact on the burden of low back pain. Yet, based on our analyses, nearly 65% of the burden would remain. The management of most low back and neck pain is largely focused on pain relief and prevention of worsening outcomes through physical therapy and exercise; given the very large burden and the associated economic consequences of lost work time, low back and neck pain should be a priority for research to identify more effective preventive and therapy measures.[52] Similarly, despite broad decreases in age-standardised rates of injury burden, the pace of progress for these causes has been comparatively slow and ultimately has led to minimal changes in the proportion of overall burden due to injuries during the last 25 years. Prevention of injuries requires strong public safety policies,[53] but minimising mortality and long-term disability from injuries hinges upon having comprehensive trauma care systems[54,55] that provide timely, evidence-based care,[56–58] including emergency surgical services.[59,60]

In 2015, sense organ disorders were the second-leading cause of YLDs and resulted in over 68 million DALYs. Reducing DALYs from vision impairment is achievable through vertically integrated programmes, including the delivery of eyeglasses for refractive error, curative surgery for cataracts, and onchocerciasis and trachoma prevention. Given the availability of cost-effective interventions, greater policy attention is needed for vision loss burden. While interventions for hearing loss are less clear-cut,

the use of timely antibiotics for otitis media and meningitis, and provision of hearing aids for individuals with conductive hearing loss, are likely to reduce its burden.

Reductions in age-standardised DALY rates due to some NCDs such as CVDs, most cancers, chronic respiratory diseases, and many digestive diseases – some of which can be attributed to reductions in risk factors such as tobacco and improvements in cause-specific treatment and event survival – mask the effects of population aging. This means more people experienced disease burden from these causes, and total DALYs have remained largely unchanged (eg, COPD) or significantly increased (eg, CVD, cancers, neurological disorders, diabetes, CKD, and musculoskeletal disorders such as oesteoarthritis and low back and neck pain) over time. As demographic transitions are widely expected to continue, the burden of NCDs is likely to continue expanding. Widespread efforts must continue to enact societal and environmental policies to reduce risk factor exposure, while national and local health systems must adapt to meet the prevention, screening, and treatment needs of their populations. As we now recognize many of the risk factors related to NCDs, low- and middle-SDI countries may have the ability to adopt policies to circumvent the mistakes made by other countries as they progressed along the SDI spectrum. Mental and substance use disorders are a particularly challenging group of conditions, with non-trivial levels of disease burden in all geographies. Some countries provide excellent mental health resources, while others – particularly LMICs – do not support screening or treatment programmes. Addressing the growing burden and disparity in mental health will be an especially pressing challenge during the SDG era.

A number of emerging and growing health threats also deserve special attention in policy planning, including infectious diseases such as dengue, Ebola, Zika, pandemic influenza outbreaks, and antimicrobial resistant pathogens, which represent acute threats to life and highlight health system deficiencies where they occur; substance abuse disorders, particularly opioids and cocaine in Eastern Europe, Australia, Latin America, and North America; and intentional firearm injuries, especially in Latin America, the US, and South Africa. In the case of dengue and potentially other to-be-identified infectious conditions, urbanization and global environmental change have contributed to an increased incidence of the disease and future climate change scenarios depict a rising trend in the coming years.[61] Other emerging infectious diseases, including Zika and chikungunya, have yet to be comprehensively analysed by the GBD.

Methods changes and data gaps

A major change in the GBD 2015 assessment has been the closer integration of the assessments of mortality and disease sequelae prevalence in modeling. For cancers, HIV/AIDS and injuries, previous iterations of the GBD modeled mortality, incidence and prevalence in a coherent manner. For some other diseases, the modeling of disease prevalence and cause-specific mortality rates largely used different data sources and modeling techniques. Independent estimation of prevalence and mortality led in some cases to patterns across locations of excess mortality rates that were not consistent with expected relationships related to health system access. For GBD 2015, we built the modeling of cause-specific mortality, excess mortality, incidence, and prevalence into nearly every cause. The effect of this approach has led to increases in the number of DALYs from injuries due to YLDs, and changes in prevalence for other conditions, particularly those with minimal data on prevalence or incidence. More attention will be paid in future iterations of the GBD to identifying unpublished data from cohort studies

or linkage studies on levels of excess mortality by age and sex, especially in LMICS, to further strengthen modeling efforts.

A major development for the GBD 2015 has been adopting GATHER guidelines endorsed by WHO, the Institute for Health Metrics and Evaluation (IHME), and other organisations.[22,23] GATHER compliance, including the sharing of statistical code for each of the many analytical steps in the GBD provides a new level of transparency for the overall enterprise. We expect that many researchers will want to investigate, propose improvements, and provide alternative assessments for many components of the GBD. We welcome the debate that will follow on the best way to analyse different components of the GBD. We believe enhanced transparency will lead to healthy debate and exchange and to improved methods, data, and results for many aspects of the GBD. Transparency will not necessarily lead to consensus but it will broaden everyone's understanding of the available evidence on descriptive epidemiology. Adoption by the GBD of the GATHER guidelines will hopefully stimulate other organisations to adopt the guidelines in all aspects of their work as well.

Although the volume of input data to the GBD has continued to increase substantially, major data gaps remain.[12,20,62,63] Geographic and temporal coverage of all-cause and cause-specific mortality datasets is variable, as is the quality of the data contained in such systems. Development of methods to report overall evidence grades for each outcome-location-year combination would be valuable to help guide strategies for improving data quality and closing data gaps. Investing to develop and improve cause of death and VR systems is crucial to improving the quality of insights from the GBD; incorporation of existing data from existing and new collaborators that is not currently in the GBD is another important aspect of this effort. Several geographies have experienced significant recent turmoil, especially armed conflict in Syria, Yemen, and other countries in North Africa and the Middle East. Burden from many conditions is believed to have increased during and following those events, but due to disruption of data collection systems, the full effect of such events has been difficult to quantify. For nonfatal health outcomes, some of the most notable data gaps pertain to aspects of individual diseases and injuries that are not typically included as part of standard epidemiological reports such as distribution of symptoms for those with chronic conditions at various stages of illness, duration of disability following acute events, or long-term disability after major acute injuries. Therefore, our recommendations regarding data gaps pertaining to nonfatal health loss are twofold. First, reports and scientific journals should strive to include reporting on functional health status including severity, distribution, and duration of symptoms with all epidemiological studies. Second, countries should work to centralise and compile existing nonfatal health data and invest to collect population-level epidemiological data on important causes of YLDs.

The iterative and now annual cycle of the GBD revisions provide opportunities to improve the estimation or scope of the GBD. Based on the broad interest in Zika, we believe that we should try to quantify the burden related to Zika in the GBD 2016 analysis. Given the focus in the SDGs on various forms of sexual violence, we believe careful investigation of the evidence base for estimation is warranted. As noted in the GBD papers on mortality and nonfatal outcomes,[12,20] there are also a number of opportunities to improve data processing and estimation methods that will be explored for the next cycle of estimation. We also expect to include more subnational analyses, particularly for large countries.

Limitations

Our analysis has several limitations. First and foremost, the calculation of DALYs and HALE reflects the limitations of all the underlying analyses of the GBD, including all-cause mortality, cause-specific mortality, prevalence, incidence, disability weight derivation, and simulation of comorbidity. Second, as discussed above, data limitations are apparent in a number of facets of our analysis. Third, inherent to the GBD approach is the effort to quantify specific sequelae of each disease and injury. This means that the full disease burden of certain conditions such as heart failure, anaemia, vision and hearing loss, infertility, epilepsy, and intellectual disability are not as readily apparent in high-level review of the GBD results. The YLDs for these impairments are reported, however, elsewhere.[20] Fourth, our analysis of the relationship between SDI, DALYs, and HALE reflects the average historical relationship between SDI and each measure, so despite often strong correlation with SDI it cannot be interpreted as being causal in nature. In some cases, association of SDI with health indicators may be considered a confounder when the same elements (education, income, fertility) are used to develop both the index and as a covariate in cause-specific models. SDI utility may be improved in the future through consideration of additional societal elements such as inequality in each component. Other measures that capture the status of women in society, such as the female labor force participation, could be considered in future revisions. Fifth, we have assumed independence of uncertainty between YLLs and YLDs as well as between YLDs and life expectancy. Empirical evidence to guide alternative assumptions, however, is currently very limited. Sixth, recent events in the Syria and Libya and the resulting mass migration have led to considerable health loss, including drownings of many migrants. New migrants have different health problems than the populations of the countries to which they have moved. Both the drownings and the change in health status in countries receiving migrants are not adequately captured in this assessment due to the time lags in data collection and data capture intrinsic in all health data systems. Seventh, estimates of expected burden based on SDI alone are based on the average levels of burden at each level of SDI. For endemic diseases, comparisons of observed rates to expected rates will lead to high observed over expected ratios in endemic countries and low ratios in non-endemic countries. Interpretation of the ratios for conditions that are endemic in only some countries needs to take this into account.

Comparison to other estimates

WHO has estimated DALYs by cause for the single years of 2000 and 2012.[13,17] They used published GBD 2010 results used to generate WHO 2012 DALYs for 132 causes with some modifications. First, WHO life tables were used instead of GBD life tables.[14] WHO life tables are different than the UN Population Division life tables and use a set of methods developed by Murray and colleagues in the late 1990s;[11,64] this approach does not benefit from the many improvements in data processing and estimation methods that have emerged in the last 15 years.[12,65,66] Second, WHO altered the empirical disability weights, which were derived from an international sample of more than 60,000 respondents from the GBD analysis,[26] for 32 outcomes using the opinions of 45 respondents.[67 13] Third, WHO calculated YLLs after changing from the GBD 2010 normative standard life expectancy of 86.0 to 91.9 years.[68] Fourth, rather than using GBD results, WHO elected to use alternative estimates for 12 causes of death, including tuberculosis, HIV/AIDS and other sexually transmitted infections, malaria, whooping cough, measles, schistosomiasis, maternal disorders, cancers, alcohol and drug use disorders, epilepsy, conflict and natural disasters, and road traffic accidents.[13] Finally, WHO substituted prevalence estimates produced internally for vision loss, hearing loss, intellectual disability, infertility, anaemia, back pain,

alcohol use disorders, headache, and skin diseases. The final hybrid estimates of DALYs do not provide uncertainty and have not been peer-reviewed.

WHO has also produced HALE estimates for three time periods – 2000, 2012, and 2015 – using GBD 2010 results as described above for 2000 and 2012, and GBD 2013 results for 2015, also without uncertainty.[14] Appendix figure 5A shows the comparison of their estimates and GBD 2015 HALE. Differences reflect changes in age-specific YLDs per capita from GBD 2013 to GBD 2015 and differences in WHO life expectancy. The European Commission and the OECD also report healthy life expectancy estimates based on self-reported health status from 2004 through 2014, but without specific consideration of prevalence or incidence of disease.[52,53] Appendix figures 5B and 5C compare 2014 estimates from the EC and GBD which in most cases show lower estimates from EC. EC estimates also report much wider ranges in HALE across countries in Europe than those estimated through GBD. Further, in a number of countries, EC estimates point to lower HALE among women than for men. These differences, both in terms of absolute estimates and those by sex, are likely due to inclusion of non-health factors in self-reported assessments of disability.

Conclusion

HALE has increased steadily throughout the world over the MDG era with a concomitant decrease in age-standardised DALY rates due to most conditions. Declines occurred in overall health loss due to many communicable, maternal, neonatal, and nutritional diseases. Much of the evolution of health is consistent with the expected changes disease burden with development that has been quantified in this study. Substantial variation in burden compared to expected levels on the basis of SDI suggest wide heterogeneity in the ability of governments and health systems to adequately meet the health needs of their populations. Progress in reducing these gaps will be critical to achieving the ambitious SDG agenda. Demographic changes leading to increased population size and older average age have offset otherwise important gains in age-specific DALY rates leading to rising burden on health systems for many "ailments of aging." Emerging health threats and causes with lagging progress should be viewed as essential foci for investment in health infrastructure and health data systems to improve the global community's insights into the aggregate quality of care and the overall health of populations.

Figures and Tables

Table 1. Global total DALYs (in thousands) and age-standardised DALY rates (per 100,000) in 2005 and 2015 with median percent change between 2005 and 2015 for all causes. Percent change for total DALYs and age-standardised DALY rates are shown with 95% UIs in parentheses. Percent changes that are statistically significant ($p < 0.05$) are shown in bold. DALYs = disability-adjusted life years. UIs = uncertainty intervals.

Table 2. Global, regional, and national or territory life expectancy and HALE at birth, by sex, in 2005 and 2015, and HALE at age 65, by sex, in 2015. 95% UIs are provided in parentheses. HALE = healthy life expectancy. UIs = uncertainty intervals. Values for countries and territories grouped into Socio-demographic Index quintiles are also provided.

Figure 1. Three views of trends 1990 to 2015 in DALYs divided by GBD level 1 cause groups: communicable, maternal, neonatal and nutritional diseases, non-communicable diseases, and injuries. Global DALYs (I, in millions), crude DALY rates (II, per 100,000 people), and age-standardised DALY rates (III, per 100,000). The difference in trends between Panels I and II is caused by population growth

and the difference between Panels II and III caused by changes in the percentage distribution of the population by age. Shaded areas show 95% UIs. DALYs = disability-adjusted life years. UIs = uncertainty intervals.

Figure 2. Leading 30 causes of global DALYs for both sexes combined for 1990, 2005, and 2015 at the GBD cause hierarchy level 3. Causes are connected by arrows between time periods. Communicable, maternal, neonatal, and nutritional disorders are shown in red; non-communicable causes in blue; and injuries in green. For the time periods 1990 to 2005 and 2005 to 2015, three measures of change are shown: percent change in the number of DALYs, percent change in the all-age DALY rate, and percent change in the age-standardized DALY rate. Mean values across the 1,000 draws from the uncertainty distribution are shown. Statistically significant changes are shown in bold.

Figure 3. Leading 10 causes of global DALYs in 2015 by age group at the GBD cause hierarchy level 3. Each cause is coloured by the percent change in age-specific DALYs from 2005 to 2015. Alzheimer = Alzheimer disease and other dementias. Anxiety = Anxiety disorders. Asthma = Asthma. Back+Neck = Low back and neck pain. CKD = Chronic kidney disease. COPD = Chronic obstructive pulmonary disease. Conduct = Conduct disorder. Congenital = Congenital anomalies. Depression = Depressive disorders. Diabetes = Diabetes mellitus. Diarrhea = Diarrheal diseases. Drown = Drowning. Drugs = Drug use disorders. Falls = Falls. HIV = HIV/AIDS. Hemog = Hemoglobinopathies and hemolytic anemias. IHD = Ischemic heart disease. Intest Inf = Intestinal infectious diseases. Iron = Iron-deficiency anemia. LRI = Lower respiratory infections. Lung C = Tracheal, bronchus, and lung cancer. Malaria = Malaria. Meningitis = Meningitis. Migraine = Migraine. NN Enceph = Neonatal encephalopathy due to birth asphyxia and trauma. NN Hemol = Hemolytic disease and other neonatal jaundice. NN Preterm = Neonatal preterm birth complications. NN Sepsis = Neonatal sepsis and other neonatal infections. Oth NN = Other neonatal disorders. PEM = Protein-energy malnutrition. Road Inj = Road injuries. STD = Sexually transmitted diseases excluding HIV. Self Harm = Self-harm. Sense = Sense organ diseases. Skin = Skin and subcutaneous diseases. Stroke = Cerebrovascular disease. TB = Tuberculosis. Violence = Interpersonal violence. GBD = Global Burden of Disease. DALYs = disability-adjusted life years.

Figure 4A. Co-evolution of healthy life expectancy with SDI for the globe and GBD regions from 1990 to 2015, with comparison to the value of expected healthy life expectancy based on SDI alone. Coloured lines show global and region values. Each point in a line represents one year starting at 1990 and ending at 2015. In all regions, SDI has increased year on year so progress in SDI is associated with later years for a given region. The black lines indicate expected trajectories for each geography expected on the basis of SDI alone. GBD = Global Burden of Disease. SDI = Socio-demographic Index. HALE = healthy life expectancy. YLDs = years lived with disability. DALYs = disability-adjusted life years.

Figure 4B. Co-evolution of functional health lost (life expectancy minus healthy life expectancy) with SDI for the globe and GBD regions from 1990 to 2015, with comparison to the value of expected functional health lost based on SDI alone. Coloured lines show global and region values. Each point in a line represents one year starting at 1990 and ending at 2015. In all regions, SDI has increased year on year so progress in SDI is associated with later years for a given region. The black lines indicate expected trajectories for each geography expected on the basis of SDI alone. GBD = Global Burden of Disease. SDI = Socio-demographic Index. HALE = healthy life expectancy. YLDs = years lived with disability. DALYs = disability-adjusted life years.

Figure 4C. Co-evolution of life expectancy spent with disability (life expectancy minus HALE, divided by HALE) with SDI for the globe and GBD regions from 1990 to 2015, with comparison to the value of expected life expectancy spent with disability based on SDI alone. Coloured lines show global and region values. Each point in a line represents one year starting at 1990 and ending at 2015. In all regions, SDI has increased year on year so progress in SDI is associated with later years for a given region. The black lines indicate expected trajectories for each geography expected on the basis of SDI alone. GBD = Global Burden of Disease. SDI = Socio-demographic Index. HALE = healthy life expectancy. YLDs = years lived with disability. DALYs = disability-adjusted life years.

Figure 5. Expected relationship between age-standardised YLL and YLD rates and SDI (A) and all-age YLL and YLD rates (per 100,000) (B) for 21 GBD level 2 causes. These stacked curves represent the average relationship between SDI and each cause observed across all geographies over the time period 1990 to 2015. In each figure, the y-axis goes from lowest SDI up to highest SDI. To the left of the midline are YLL rates and the right-hand side shows rates for YLDs; higher rates are further from the midline. The difference between A and B is the effect of shifts in population age structure expected with SDI. GBD = Global Burden of Disease. SDI = Socio-demographic Index. YLDs = years lived with disability. YLLs = years of life lost.

Figure 6. Ratio of observed versus expected age-standardised DALY rates (per 100,000) on the basis of SDI alone for both sexes combined, 2015. SDI = Socio-demographic Index. DALY = disability-adjusted life year.

Figure 7. Leading 10 causes of DALYs, by country and territory, in 2015 at the GBD cause hierarchy level 3. The ratio of observed DALYs to DALYs expected on the basis of SDI alone is provided in brackets for each cause, and are colour-coded by the ratio of observed DALYs to expected DALYs, on the basis of SDI alone. Alcohol = Alcohol use disorders. Alzheimer = Alzheimer's disease and other dementias. Anxiety = Anxiety disorders. Back+Neck = Low back and neck pain. Cirr HepC = Cirrhosis due to hepatitis C. CKD = Chronic kidney disease. CMP = Cardiomyopathy and myocarditis. Colorect C = Colon and rectum cancer. Congenital = Congenital anomalies. COPD = Chronic obstructive pulmonary disease. Depression = Depressive disorders. Diabetes = Diabetes mellitus. Diarrhoea = Diarrhoeal diseases. Drown = Drowning. Drugs = Drug use disorders. F Body = Foreign body. Hemog = Haemoglobinopathies and hemolytic anaemias. HIV = HIV/AIDS. HTN HD = Hypertensive heart disease. IHD = Ischemic heart disease. Iron = Iron-deficiency anaemia. Liver C = Liver cancer. LRI = Lower respiratory infections. Lung C = Lung, bronchus, and trachea cancer. Nematode = Intestinal nematode infections. NN Enceph = Neonatal encephalopathy due to birth asphyxia and trauma. NN Preterm = Preterm birth complications. NN Sepsis = Neonatal sepsis and other neonatal infections. Oth Cardio = Other cardiovascular and circulatory diseases. Oth MSK = Other musculoskeletal disorders. Oth NN = Other neonatal disorders. PEM = Protein-energy malnutrition. Road Inj = Road injuries. Sense = Sense organ diseases. Skin = Skin and subcutaneous diseases. STD = Sexually transmitted diseases excluding HIV. Stomach C = Stomach cancer. Stroke = Cerebrovascular disease. TB = Tuberculosis. Violence = Interpersonal violence. War = Collective violence and legal intervention. GBD = Global Burden of Disease. SDI = Socio-demographic Index. DALYs = disability-adjusted life years.

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